

## Space Weather and Solar Wind Studies with OWFA

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**Abstract.** In this paper, we review the results of interplanetary scintillation (IPS) observations made with the legacy system of the Ooty Radio Telescope (ORT) and compare them with the possibilities opened by the upgraded ORT, the Ooty Wide Field Array (OWFA). The stability and the sensitivity of the legacy system of ORT allowed the regular monitoring of IPS on a grid of large number of radio sources and the results of these studies have been useful to understand the physical processes in the heliosphere and space weather events, such as coronal mass ejections, interaction regions and their propagation effects. In the case of OWFA, its wide bandwidth of 38 MHz, the large field of view of  $\sim 27^\circ$  and increased sensitivity provide a unique capability for the heliospheric science at 326.5 MHz. IPS observations with the OWFA would allow one to monitor more than 5000 sources per day. This, in turn, will lead to much improved studies of space weather events and solar wind plasma, overcoming the limitations faced with the legacy system. We also highlight some of the specific aspects of the OWFA, potentially relevant for the studies of coronal plasma and its turbulence characteristics.

*Key words:* radio interplanetary scintillation - solar wind, turbulence - space weather events, coronal mass ejections, propagation, disturbances, shock waves

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## 1. Introduction

One of the successful observational programs being carried out for many years at the Ooty Radio Telescope (ORT) is to determine the three-dimensional structure, evolution and dynamics of quiet and transient solar wind in the Sun-Earth space by using interplanetary scintillation (IPS). These studies have provided valuable inputs to the solar physics community to understand the physical processes in the heliosphere and space weather events, such as coronal mass ejections (CMEs), interaction regions and their propagation effects. These studies have also provided a basis to develop models to predict the effects of such events at 1 AU (e.g., Manoharan 2006; Vršnak et al. 2008). However, the present sampling of the heliosphere by the ORT in a day limits the accuracy of such models. It is important to improve on this situation because the practical consequences of space weather demand advance and accurate prediction of space weather effects associated with energetic CMEs. For example, large and high speed Earth-directed CMEs are now considered to be the major source of transient interplanetary disturbances and shocks, which could cause severe geo-magnetic storms and lead to adverse effects on many crucial technological systems (e.g., Kumar et al. 2011).

A recent important concern of the solar physics is that a wide array of ground- and space-based observations show that the Sun has entered a sustained period of low activity (e.g., Manoharan 2012; Basu 2016). The current solar cycle #24 seems to be the smallest sunspot cycle observed since cycle #14, which was observed around the beginning of year 1906. The effects of low magnetic activity are observed throughout the heliosphere. Among the prominent effects of this is that the cosmic ray flux near the Earth reached the highest level in the recent past. This in turn leads to various effects in the Earth's atmosphere. The state of the interplanetary medium associated with the low solar activity may also influence the effects of propagation of CMEs, formation of shocks, etc., (e.g., Manoharan et al. 2016). Thus, an improved global monitoring of the solar wind and transients as well as the space weather conditions at the near-Earth distances would be highly timely.

## 2. Solar Wind Measurements

Solar wind observations, to date, have been made mainly in two ways, viz.: (1) directly by *in-situ* sampling of the downstream plasma, (2) remotely, through radio spectroscopy, and radio sounding observations. Since the 1960s a large number of spacecraft have successfully conducted routine *in-situ* sampling of the solar wind (e.g., speed, density, temperature, composition, and magnetic field) in the near-Earth space and beyond. However, *in-situ* measurements are limited to the one-dimensional time scan at the location of the spacecraft. Proper measurements of spatial and tem-

poral variations would require a grid of space missions. Moreover, spacecraft sampling is largely confined to the ecliptic plane. Ulysses was the first and only space mission that probed the high latitude heliosphere (e.g., McComas et al. 2008).

However, the typical flow of the solar wind and the propagation of solar-generated transients show considerable changes with heliolatitude as well as distance from the Sun. For example, the eruption of a CME/flare event, originating from the complex magnetic region on the Sun, adds significant amount of mass and magnetic field to the solar wind. The propagating transient associated with the CME is about a solar radius in size at the near-Sun region and it can expand to a structure of about an AU in the near-Earth environment (e.g., Manoharan et al. 2000). Additionally, CME associated transients can involve: (1) acceleration of electrons and ions to high energies, (2) formation and steepening of interplanetary forward/reverse shocks at distances from the Sun, and (3) propagating/expanding large-scale magnetic clouds (i.e., flux ropes) (e.g., Manoharan 2006; Manoharan and Agalya 2011). Thus, a high occurrence rate of intense flare/CME events can result in the complex flow of solar wind of different time and spatial scales. Therefore, the study of global properties of the solar wind and the efficient tracking of a transient event (as well as in understanding its interaction with the ambient solar wind as a function of distance from Sun) demand solar wind observations at consecutive parts of the heliosphere and we need to employ techniques and/or observations other than that of *in-situ* measurements from a satellite, which is normally confined to the orbit of the Earth. The radio remote-sensing technique, e.g., interplanetary scintillation, can provide estimates of solar wind speed and density turbulence in the three-dimensional space. However, remote-sensing measurements probe the solar wind plasma integrated along the line of sight and hence require care in the interpretation.

## 2.1 Interplanetary Scintillation Technique

The IPS technique exploits scattering of radiation from compact radio sources (i.e., radio quasars and galaxies of angular size,  $\Theta < 500$  milliarcsecond (mas)) by small-scale ( $< 1000$  km) density inhomogeneities in the solar wind (e.g., Hewish et al. 1964; Coles 1978; Manoharan 1993). Since the drift of solar wind density inhomogeneities across the line of sight to the source causes intensity scintillation (typically, intensity fluctuations are observed on timescales of  $\sim 0.1$ –10 seconds), the shape of the IPS power spectrum is related to the bulk velocity of the density structures and their scale sizes. The power spectrum of intensity fluctuations can be suitably calibrated to estimate the solar wind speed, the level of density turbulence, and the dominant scales present at the region of closest solar approach of the line of sight to the radio source (e.g., Manoharan 1993, 2012; Manoharan and Ananthakrishnan

1990; Manoharan et al. 2000; Tokumaru et al. 1994). Thus, the regular monitoring of the IPS of a given radio source using a single-antenna system of good sensitivity can provide the speed and density turbulence of the solar wind at a range of heliocentric distances (i.e., as the source gradually approaches and recedes the Sun). Additionally, using IPS one can do day-to-day monitoring of the heliosphere on a grid of large number of radio sources, whose lines of sight cut across different parts of the heliosphere. The Ooty Radio Telescope is well suited for such monitoring of the inner heliosphere.

## 2.2 IPS with the Ooty Radio Telescope

The Ooty Radio Telescope (ORT) is an equatorially mounted steerable cylindrical paraboloid (530 m  $\times$  30 m) (Swarup et al. 1971), operating at a central frequency of 326.5 MHz. The legacy system of the ORT provides a resolution of  $2^\circ \times 6'$ , in the east-west and north-south directions, respectively. The ORT covers  $-4^{\text{h}}7^{\text{m}}$  to  $+5^{\text{h}}25^{\text{m}}$  in hour angle and  $\pm 65^\circ$  in declination. The ORT is also supported with a beam-forming system of 12 simultaneous equispaced beams. Each beam is separated by  $3'$ . For a given declination pointing, this system provides a sky coverage of  $36'$  in the north-south direction (Sarma et al. 1975; Selvanayagam et al. 1993). Over the last several years, IPS observations made with the ORT have been efficiently used to study the dynamics of the interplanetary medium on time scales ranging from a few hours to years.

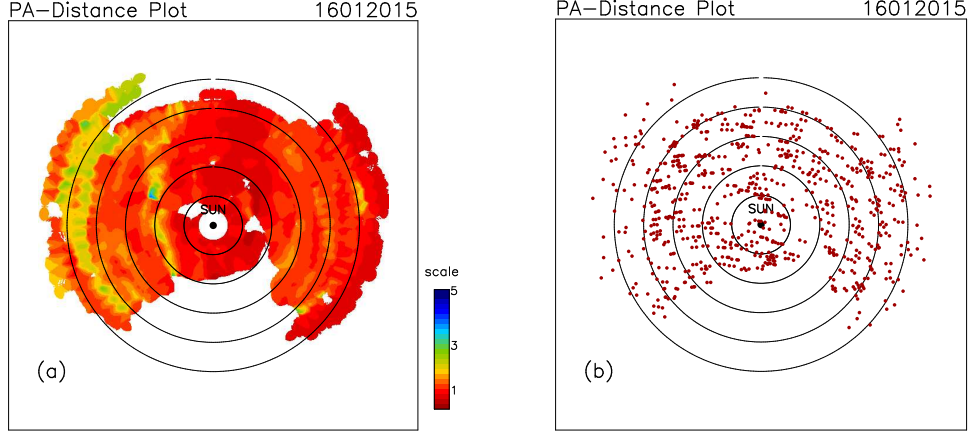
In the IPS observing mode, since the ORT is fully steerable in the east-west direction, a given scintillating source can be continuously tracked for  $\sim 09^{\text{h}} 30^{\text{m}}$  (i.e., from the rise time of the source at the east limit of the ORT to its set time at the west limit) and the solar wind condition along the direction of the source can be monitored in details. In the above span of observing time, the change in the position of the source with respect to the Sun is not significant (i.e., typically a source moves with respect to the Sun by  $\sim 1$  degree per day) and the continuous tracking observation essentially provides the parameters of the solar wind along a fixed line of sight. On the other hand, to scan the solar wind over a wide area of the sky, the ORT can be parked at a convenient hour angle and each source transiting at the telescope can be observed for about 90 seconds by just electronically switching the north-south beam. A sufficient time gap, if available between the observations of two consecutive sources, can be used to observe the off-source level of IPS, which is required for the estimation of the scintillation index of each observed source (Manoharan 1993; Manoharan et al. 1995). In a regular mode of solar wind monitoring, a parking hour angle is chosen close to the east limit of ORT ( $-4^{\text{h}}$ ), which can include the global monitoring of regions, respectively, in the western side of the Sun, close to the Sun, and in the eastern side of the Sun. In such an observing mode, depending on the duration of observation (e.g., 6–8 hours), the scintillating sources monitored

can cover a wide range of heliolatitudes as well as heliocentric distances in the range of 20–250  $R_{\odot}$  in the west as well as east of the Sun and a CME and its associated disturbances propagating in any direction with respect to the Sun can be recorded. Further, the steerability of the ORT allows us to monitor the same part of the sky by parking the ORT, respectively, at hour angles overhead ( $0^h$ ) and near the west limit ( $+4^h$ ) and provides the opportunity to study the temporal and radial evolution of the CME for a period of  $\sim 20$  hours (e.g., Manoharan et al. 2000, 2001). Alternatively, if an *a priori* information on the propagation direction of a CME is known, the ORT can also be parked at an appropriate hour-angle position and the scintillation of the drifting sources can be studied for a duration of up to  $\sim 20$  hours, which can also cover a wide heliocentric distances in the west and east of the Sun.

Moreover, for a given central beam setting of a radio source, the 12-beam system of the ORT often includes one or more sources at other beams away from the central beam and such observations increase the number of sources monitored at a given time. By combining the above hour angle scans, a good spatial resolution in the sky plane is achieved. In the recent past, depending on the other observing programs, the ORT has been used to make daily observations of about 600–900 radio sources, covering a distance range  $\sim 20$ –250  $R_{\odot}$  (corresponding to a solar elongation range of  $\sim 5^{\circ}$ – $100^{\circ}$ ) in the western and eastern sides of the Sun. The above set of sources monitored normally includes nearly  $\sim 90\%$  of scintillators and the remaining are non-scintillators (sources having large angular sizes,  $\Theta > 500$  mas). The extended sources are not influenced by the solar wind conditions and are monitored to check the contamination caused by the ionospheric plasma and the level of radio frequency interferences (RFIs), if present. It is to be noted that the ionospheric scintillation, which is rare at 326.5 MHz during the daytime, has different timescales from that of IPS and can also be easily eliminated from the IPS power spectrum.

In the past, a good fraction of the ORT time was used for IPS observations. The regular long-term monitoring of IPS on several radio sources has in fact provided the “*scintillation index – heliocentric distance*” curves of all these sources for several years. Ooty scintillation-index curves are available for  $\sim 8000$  radio sources and these can be used to estimate the typical one-dimensional angular diameter of the compact component of each source as well as its flux density at 326.5 MHz (Manoharan et al., *in preparation*). Additionally, the scintillation curves obtained from the ORT have been made available to IPS groups at the Solar-Terrestrial Environment Laboratory, Nagoya University, Japan (Tokumaru et al. 2011) and the Mexican IPS Radio Array at the University of Mexico, Mexico (González-Esparza et al. 2004).

Ooty IPS studies have led to several important results on – (1) understanding otherwise unavailable information on the three-dimensional shape



**Figure 1.** (a) An example of scintillation image observed with the ORT on 16 January 2015 (left plot). It shows the sky-plane projection of observed levels of density turbulence in the solar wind in the inner heliosphere and the Sun is at the centre of the image. The red color code indicates the background solar wind and the enhanced scintillation patches indicate the presence of interplanetary CMEs in the IPS field of view. (b) A similar plot shown in the right is the distribution of IPS sources observed to make the scintillation image and each dot represents the position of a radio source. The plotted IPS field of view includes  $\sim 600$  radio sources. In these “*position angle (PA) – heliocentric distance*” plots, the north is at the top, i.e.  $PA = 0^\circ$  and  $PA$ s  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ , respectively, correspond to the east, south, and west of the Sun. Observing time increases from the right-hand side of the plot (i.e., from the west of the Sun) to the left-hand side (i.e., the east of the Sun). The concentric circles are of radii, 50, 100, 150, 200, and  $250 R_\odot$ .

and dynamics of the large-scale structures of CME-associated disturbances in the Sun-Earth space (e.g., Manoharan 2010); (2) clearly establishing the speed and associated magnetic structure of CMEs as well as the background solar wind, which are crucial to understand the effects of the CME at the near-Earth environment (Manoharan et al. 2001; Manoharan 2006) and these studies have led to the development of propagation models to predict the effects of CME events at  $\sim 1$  AU (e.g., Mays et al. 2015); (3) the relationship between the speed and transit time of CME-associated disturbances; (4) the three-dimensional evolution of density turbulence and speed of quasi-stationary solar wind at various levels of solar activity over a period of three decades (e.g., Manoharan 1993, 2012); (5) a better understanding of the nature of turbulence and plasma processes of the ambient solar wind in the inner heliosphere and the solar wind plasma associated with the interplanetary disturbance (e.g., shape of the density turbulence spectrum and its dissipative scales as the function of distance from the Sun) (Manoharan et al. 1994, 2000, 1987).



### 2.3 IPS Imaging with the Legacy ORT System

Figure 1a shows example of a scintillation image obtained with the ORT based on observations of about 600 IPS sources on 16 January 2015. These observations were taken over a time period of  $\sim 18$  hours at an hour-angle pointing of  $0^h$  and nearly equal regions were sampled in the western and eastern hemispheres of the heliosphere. This plot is the sky-plane snapshot image of level of density turbulence in solar wind, observed over a heliocentric distance range of more than an AU from the Sun. (For more details on the Ooty IPS analysis and the construction of scintillation image, the reader may refer to Manoharan et al. (2001).) The image area is made of  $600 \times 600$  pixels (i.e., covering a heliosphere diameter about 3 AU). Since the image is made from scintillation observations of a large number of discrete radio sources, it has been smoothed by a two-dimensional Gaussian of width  $20 \times 20$  pixels. The radius of the concentric circles drawn around the Sun increases in steps of  $50 R_\odot$ . The orbit of the Earth is located at  $\sim 215 R_\odot$ . The observing time increases from the right of the image (the west of the Sun) to the left (the east of the Sun). The red color code indicates the background (i.e., ambient) solar wind. The enhanced scintillation regions represent the CME-driven disturbances and/or interactions between slow and fast solar wind streams. For example, the propagation of two CMEs that originated from the Sun on 13 and 15 January 2015 are seen in the north-east direction of the Sun, respectively, at  $\sim 225 R_\odot$  and  $100 R_\odot$ . Apart from these, some more faint enhanced features are also identifiable in Figure 1a.

As mentioned above, this scintillation image has been made from IPS observations of  $\sim 600$  radio sources and the distribution of these sources around the Sun is shown in Figure 1b (right-hand side plot). Each dot in the plot corresponds to a radio source. The noted asymmetry in the source distribution between the north and south regions of the heliosphere is due to the allowed declination coverage of  $\pm 60^\circ$  for the above IPS measurements (i.e., at high declinations,  $> |\pm 45^\circ|$ , the sensitivity of the ORT is severely affected by the decrease in the projected collecting area). The radio sources employed are of flux density  $\geq 1$  Jy at 326.5 MHz. It may be noted that the overall source distribution is not uniform and there are several small to large gaps seen in the plot. In particular at heliocentric distances  $> 150 R_\odot$ , the number of sources observed is less than that observed at small distances from the Sun. This is mainly due to the fact that the radial falloff of the power of density turbulence in the solar wind is rather steep,  $C_{N_e}^2(R) \sim R^{-4}$ , and the scintillation of a source would also decrease with the distance from the Sun in the above manner. At 326.5 MHz, for a point source (e.g.,  $\Theta \leq 20$  mas), the maximum level of scintillation is observed at  $\sim 40 R_\odot$  and it is reduced by an order of magnitude at  $\sim 150 R_\odot$  (Manoharan et al. 1995). In the present legacy system of the ORT, we employ a receiver system bandwidth of  $\sim 4$  MHz centered around 326.5 MHz and use an integration time

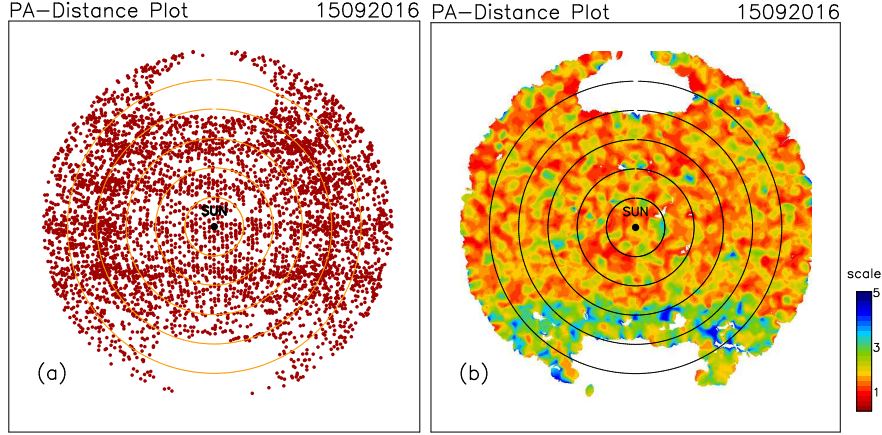
on each source of  $\sim 90$  seconds. This enables the detection of a scintillation flux of  $\sim 25$  mJy. In the legacy system, for a given observing period, the number of sources observed is therefore limited by their compact component flux densities as well as angular sizes. However, the Gaussian smoothing function used to smooth an image area of  $\sim 20 \times 20$  pixels enables the detection of overall large-scale structures of the three-dimensional solar wind. Further, CMEs in general propagate with high speed (i.e., speed in excess of the background solar wind speed of  $\sim 300\text{--}350$   $\text{kms}^{-1}$ ) and the present spatial resolution provided by the distribution of sources is just enough to sample the propagating CME structures at a couple of places in the inner heliosphere (e.g., Manoharan et al. 2001). Thus, IPS observations with the present legacy system have limited the detailed inference of the small-scale features of solar wind, CMEs, and interaction regions. Another important point is that the temporal cadence obtained for a fast moving CME in a day is low and hence precise study of such fast moving CMEs is difficult with the present IPS measurements alone.

### 3. IPS with the Ooty Wide Field Array (OWFA)

In order to improve the study of fine features of CMEs, solar wind structures and to predict their arrival times and associated consequences at the near-Earth space about a day in advance, the essential requirement is the imaging of the interplanetary medium with further increased spatial and temporal resolutions. In comparison with the legacy ORT system, the upgraded OWFA has both a large instantaneous bandwidth of  $\sim 38$  MHz and a significantly wide north-south beam of  $\sim 27^\circ$  (refer to Subrahmanya, Manoharan, and Chengalur 2016, *in this volume*). For example, at a given time, the large declination coverage of the OWFA beam would allow the simultaneous observation of a number of IPS sources covered within its beam. Additionally, the increase in the sensitivity of the OWFA by a factor  $\sim 3$  would enable the observation of sources with weak scintillating flux density.

The OWFA will have an FX correlator with a bandwidth of  $\sim 38$  MHz and with 800 spectral channels (Subrahmanya, Manoharan & Chengalur, 2016, JApA (*submitted*); Subrahmanya & Chengalur 2016 (*in preparation*)). Phased array beam formation will be done post-correlation. Since the OWFA baselines are highly redundant, (with only 264 of the 34716 baselines being unique) the post correlation beam formation can be done highly efficiently. The visibility on the each of the unique baselines can be estimated by averaging over the multiple redundant copies. The data volume is now so drastically reduced that one can form simultaneous phased array beams covering the entire field of view corresponding to the primary beam of the individual OWFA elements. All sources of interest lying within the primary beam can hence be simultaneously monitored. This real-time beam forming





**Figure 2.** (a) A simulated source distribution possible with the OWFA for an IPS monitoring on 15 September 2016. It includes  $\sim 5500$  radio sources and each dot on the plot corresponds to a radio source. (b) The simulated scintillation image obtained for the above source distribution. These plots are similar to the format of Figure 1.

requires high cadence, real-time calibration of the antenna gains, for which fast redundancy calibration algorithms have been developed and tested for OWFA (Marthi and Chengalur 2014).

For the parameters of the OWFA system, a simulated source distribution (for observations on 15 September 2016) is shown in Figure 2a. The source lists used for making the above simulation include (1) the existing list of IPS scintillators obtained from the ORT long-term monitoring, which includes sources of flux density  $\geq 1$  Jy at 326.5 MHz, and (2) sources of flux density  $\geq 0.7$  Jy at 326.5 MHz, scaled from the Texas and Molonglo surveys, respectively, made at 365 and 408 MHz (Douglas et al. 1996; Large et al. 1981). This simulation has been done for an hour-angle pointing of  $\sim 0^{\text{h}}$  and an observing time span of  $\sim 18$  hours, centered around the transit time of the Sun on 15 September 2016 and it is generated for an observing situation similar to that presented in Figure 1. The OWFA beam has been scanned from  $-65^{\circ}$  to  $+65^{\circ}$  in a step of  $\sim 20^{\circ}$ , which allows considerable overlap between one beam setting to the other. In a beam setting, all the sources of flux density  $\geq 0.7$  Jy contained in the primary beam area of  $2^{\circ} \times 27^{\circ}$  are considered. However, if more than one source is located within the beam size of the full ORT,  $2^{\circ} \times 6'$ , it is counted as a single source. The number of sources included in the simulated distribution is more than 5500, which is about an order of magnitude larger than the number of sources observed with the legacy system (refer to Figure 1). In comparison with the legacy system, the above source distribution obtained for the OWFA nearly fills the imaged area and large gaps are almost absent. Since the improved sensitivity

of the OWFA allows the observations of sources with small scintillating flux density, the simulated coverage looks nearly uniform throughout the 3-AU heliosphere. It is to be noted that the above simulation includes only sources of  $S_{326.5} \geq 0.7$  Jy. But, since IPS is not much limited by the confusion limit of the system, the OWFA can therefore observe sources weaker than the above limit. Since the number density of the source increases with decreasing flux density, the IPS with the OWFA is expected to provide more finer spatial resolution than that discussed above.

Figure 2b shows the typical two-dimensional image obtained from the above simulated source distribution. In order to make this image, a uniform level of 50% of the source flux density is taken as the level of scintillation and the maximum allowed scintillation is limited at 5 units. It is equivalent to Figure 1a and covers an area of  $600 \times 600$  pixels. The simulated image has been smoothed by a two-dimensional Gaussian of width  $5 \times 5$  pixels, which is 16 times smaller than the area used in smoothing the image obtained with the legacy system (refer to Figure 1). It is evident that the image is not smooth and shows number of fine features. Such an image on a short observing time span will provide information on small-scale structures embedded within a CME as well as their evolution characteristics. The quick scanning of the OWFA beam would also allow to image the fast moving CMEs and study their dynamics with the IPS measurements alone.

IPS observations of small flux density sources aimed with the OWFA are also likely to lead to the detection of ultra compact radio sources possibly at high red shift. The increase in sensitivity of the OWFA by a factor of  $\sim 3$  not only enables the observation of small flux density sources, but will also provide an excess of  $\sim 5$  dB signal in the estimated power spectrum (e.g., Naidu et al. 2015). This will be useful to infer the characteristics of small dissipative scales (i.e., at scales  $< 25$  km (Manoharan et al. 1994, 2000, 1987)) of the density turbulence. These studies are crucial to understand the evolution of density turbulence and the behaviour of the dissipative scales in the solar wind, which, in turn are essential to understand the physical processes associated with the solar wind plasma. The turbulence spectrum can also be studied as functions of (1) distance from the Sun, (2) heliographic latitude or source region of solar eruption, and (3) solar activity phase.

### 3.1 *Reconstruction of Heliosphere*

Since the IPS with the legacy system provides observations on a grid of large number of sources per day, it allows the reconstruction of the three-dimensional heliosphere using the time-dependent computer-assisted tomography technique (CAT) developed at the University of California, San Diego (e.g., Manoharan 2010; Jackson et al. 2003). The basic data sets required for the three-dimensional reconstruction are the time series of solar wind speed and level of scintillation for a large number of lines of sight of the

heliosphere. Even with the limited number of lines of sight, the reconstructions made with the legacy system of the ORT have given several important results (Bisi et al. 2009; Manoharan 2010). The much better coverage of the OWFA would hence provide an improved understanding of the dynamic heliosphere.

### 3.2 IPS Picket Fencing with the OWFA

In order to probe fine structure in a CME, the legacy ORT system was employed in a couple of special type of IPS observations, in which only a few IPS sources (i.e., only two or three lines of sight) were selected such that to lie at the expected crossing location of the radially moving CME and its associated interplanetary disturbance. The continuous monitoring of a few radio sources at frequent interval (about 2 min on each line of sight) allows one to estimate (1) ambient solar wind before the arrival of the CME at the IPS lines of sight; (2) the properties of plasma along the radial cut through the shock, sheath, and CME; (3) the upstream flow behind the interplanetary disturbance (Manoharan 2010).

Even though IPS measurements are integrated along a line of sight, they are still useful to study the characteristics of the plasma within the CME and the solar wind moving ahead and behind the disturbance. The CME study using this ‘picket-fence’ method with the OWFA will allow observations of large number of lines of sight for a given distance from the Sun. For example, in Figure 2a, if we consider a circular ring of constant radius running from the north pole to south pole of the inner heliosphere, several sources will lie on the circular ring. The simple beam switching between these sources would provide high cadence sampling, at times before, during a CME passage, and after its crossing. Such set of observations at two or more radial distances can give detailed information on (1) internal structure of the CME and its variations as a function of radial distance, (2) overall size of the CME and its evolution with distance, (3) the shock forming location in front of the CME, (3) stand-off distance/time (i.e., distance or time between the driver gas and the shock), and (4) dynamics of the shock and sheath. Such studies can also be useful to infer the particle acceleration site as well as the effective acceleration encountered by the CME in the solar wind (Manoharan 2006). They are also vital to understand the energy of the solar wind as well as the energy transfer between the disturbance and the surrounding ambient medium.

As in the picket-fence method, if we examine the circular rings of varying radii at the polar regions above the Sun, it can provide new information on the fine structure of polar plumes, their temporal evolution and relationship with other transient phenomena. Polar plumes are thin long ray kind of structures observed above the polar coronal holes and they can extend up to a distance of several solar radii. The OWFA would help to observe the polar

solar wind on much finer spatial and temporal scales, allowing the study of plasma processes associated with the polar plumes. In a similar way, OWFA IPS program will also help to investigate the plasma associated with coronal jets above the limb of the Sun. Such studies could be essential in understanding the plasma processes linked to the coronal heating problem.

#### 4. Summary

In this paper, we briefly discuss the ongoing IPS observing program with the legacy system of the ORT and its limitations in understanding the details of physical processes associated with CMEs and the solar wind in the Sun-Earth distance range. The upgraded ORT, the OWFA, will have a large field of view and improved sensitivity and allow observations of about an order of magnitude large number of IPS sources. Thus, its unique ability to sample large areas of the interplanetary medium with unprecedented spatial and temporal resolutions gives the OWFA advantages over all current radio telescopes. The OWFA can be potentially useful in addressing, but not limited to, the following studies: (1) it can enhance the inference of dynamics of space weather events, in particular, fast moving CMEs and improve the predictability of their arrival at the near-Earth space; (2) The tomographic reconstruction of IPS with OWFA is expected to provide a clear view of the global heliosphere; (3) Detailed IPS studies on limited number of radio sources can be useful to probe different parts of a CME, its associated shock, sheath, and their influence on the surrounding ambient solar wind; (4) The capability of OWFA also allows to select a given region of the heliosphere and investigate its plasma characteristics.

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#### References

- S. Basu. Global seismology of the sun. *Living Reviews in Solar Physics*, 13 (2), August 2016. doi: 10.1007/s41116-016-0003-4.
- M. M. Bisi, B. V. Jackson, J. M. Clover, P. K. Manoharan, M. Tokumaru, P. P. Hick, and A. Buffington. 3-d reconstructions of the early-november 2004 cdaw geomagnetic storms: analysis of ooty ips speed

- and density data. *Ann. Geophys.*, 27:4479–4489, December 2009. doi: 10.5194/angeo-27-4479-2009.
- W. A. Coles. Interplanetary scintillation. *Space Science Reviews*, 21:411–425, February 1978. doi: 10.1007/BF00173067.
- J. N. Douglas, F. N. Bash, F. A. Bozayan, G. W. Torrence, and C. Wolfe. The texas survey of radio sources covering  $-35.5$  degrees  $<$  declination  $<$  71.5 degrees at 365 MHz. *Astronomical Journal*, 111:1945, May 1996. doi: 10.1086/117932.
- J. A. González-Esparza, A. Carrillo, E. Andrade, R. Pérez-Enríquez, and S. Kurtz. The MEXART interplanetary scintillation array in Mexico. In *Geofis. Int.*, pages 61–73, 2004.
- A. Hewish, P. F. Scott, and D. Wills. Interplanetary scintillation of small diameter radio sources. *Nature*, 203:1214–1217, September 1964. doi: 10.1038/2031214a0.
- B. V. Jackson, P. P. Hick, A. Buffington, M. Kojima, M. Tokumaru, K. Fujiki, T. Ohmi, and M. Yamashita. Time-dependent tomography of hemispheric features using interplanetary scintillation (IPS) remote-sensing observations. In M. Velli, R. Bruno, F. Malara, and B. Bucci, editors, *Solar Wind Ten*, volume 679 of *American Institute of Physics Conference Series*, pages 75–78, September 2003. doi: 10.1063/1.1618545.
- P. Kumar, P. K. Manoharan, and W. Uddin. Multiwavelength study on solar and interplanetary origins of the strongest geomagnetic storm of solar cycle 23. *Solar Physics*, 271:149–167, July 2011. doi: 10.1007/s11207-011-9805-7.
- M. I. Large, B. Y. Mills, A. G. Little, D. F. Crawford, and J. M. Sutton. The molonglo reference catalogue of radio sources. *MNRAS*, 194:693, February 1981. doi: 10.1093/mnras/194.3.693.
- P. K. Manoharan. Three-dimensional structure of the solar wind: Variation of density with the solar cycle. *Solar Physics*, 148:153–167, November 1993. doi: 10.1007/BF00675541.
- P. K. Manoharan. Evolution of coronal mass ejections in the inner heliosphere: A study using white-light and scintillation images. *Solar Physics*, 235:345–368, May 2006. doi: 10.1007/s11207-006-0100-y.
- P. K. Manoharan. Ooty interplanetary scintillation - remote-sensing observations and analysis of coronal mass ejections in the heliosphere. *Solar Physics*, 265:137–157, August 2010. doi: 10.1007/s11207-010-9593-5.

- P. K. Manoharan. Three-dimensional evolution of solar wind during solar cycles 22–24. *The Astrophysical Journal*, 751(2):128, May 2012.
- P. K. Manoharan and G. Agalya. High Energy Solar Particle Events and Their Associated Coronal Mass Ejections. *Advances in Geosciences, Volume 27: Solar Terrestrial (ST)*, 27:165–179, July 2011.
- P. K. Manoharan and S. Ananthakrishnan. Determination of solar-wind velocities using single-station measurements of interplanetary scintillation. *MNRAS*, 244:691–695, June 1990.
- P. K. Manoharan, S. Ananthakrishnan, and A. Pramesh Rao. Ips observations of solar wind in the distance range 40–200  $R_{sun}$ . In V. J. Pizzo, T. Holzer, and D. G. Sime, editors, *Sixth International Solar Wind Conference*, pages 55–57, 1987.
- P. K. Manoharan, M. Kojima, and H. Misawa. The spectrum of electron density fluctuations in the solar wind and its variations with solar wind speed. *Journal of Geophysical Research*, 99:23411–23420, Dec 1994. doi: 10.1029/94JA01955.
- P. K. Manoharan, S. Ananthakrishnan, M. Dryer, T. R. Detman, H. Leinbach, M. Kojima, T. Watanabe, and J. Kahn. Solar wind velocity and normalized scintillation index from single-station ips observations. *Solar Physics*, 156:377–393, February 1995. doi: 10.1007/BF00670233.
- P. K. Manoharan, M. Kojima, N. Gopalswamy, T. Kondo, and Z. Smith. Radial evolution and turbulence characteristics of a coronal mass ejection. *ApJ*, 530:1061–1070, February 2000. doi: 10.1086/308378.
- P. K. Manoharan, M. Tokumaru, M. Pick, P. Subramanian, F. M. Ipavich, K. Schenk, M. L. Kaiser, R. P. Lepping, and A. Vourlidas. Coronal mass ejection of 2000 july 14 flare event: Imaging from near-sun to earth environment. *ApJ*, 559:1180–1189, October 2001. doi: 10.1086/322332.
- P. K. Manoharan, D. Maia, A. Johri, and M. S. Induja. Interplanetary Consequences of Coronal Mass Ejection Events Occurred During 18-25 June 2015. In I. Dorotovic, C. E. Fischer, and M. Temmer, editors, *Coimbra Solar Physics Meeting: Ground-based Solar Observations in the Space Instrumentation Era*, volume 504 of *Astronomical Society of the Pacific Conference Series*, pages 59–66, April 2016.
- V. R. Marthi and J. Chengalur. Non-linear redundancy calibration. *MNRAS*, 437:524–531, January 2014. doi: 10.1093/mnras/stt1902.
- M. L. Mays, A. Taktakishvili, A. Pulkkinen, P. J. MacNeice, L. Rastätter, D. Odstrcil, L. K. Jian, I. G. Richardson, J. A. LaSota, Y. Zheng,



- and M. M. Kuznetsova. Ensemble modeling of cmes using the wsa-enlil+cone model. *Solar Physics*, 290:1775–1814, June 2015. doi: 10.1007/s11207-015-0692-1.
- D. J. McComas, R. W. Ebert, H. A. Elliott, B. E. Goldstein, J. T. Gosling, N. A. Schwadron, and R. M. Skoug. Weaker solar wind from the polar coronal holes and the whole sun. *Geophysical Research Letters*, 35(18): L18103, 2008. doi: 10.1029/2008GL034896.
- A. Naidu, B. C. Joshi, P. K. Manoharan, and M. A. Krishnakumar. PONDER - a real time software backend for pulsar and ips observations at the Ooty Radio Telescope. *Experimental Astronomy*, 39:319–341, June 2015. doi: 10.1007/s10686-015-9450-5.
- N. V. G. Sarma, M. N. Joshi, D. S. Bagri, and S. Ananthakrishnan. Receiver system of the Ooty Radio Telescope. *IETE Journal of Research*, 21(3): 110–116, 1975. doi: 10.1080/03772063.1975.11450642.
- A. J. Selvanayagam, A. Praveenkumar, D. Nandagopal, and T. Veluswamy. Sensitivity boost to the Ooty Radio Telescope: A new phased array of 1056 dipoles with 1056 low noise amplifiers. *IETE Technical Review*, 10: 333–339, July 1993.
- G. Swarup, N. V. G. Sarma, M. N. Joshi, V. K. Kapahi, D. S. Bagri, S. H. Damle, S. Ananthakrishnan, V. Balasubramanian, S. S. Bhawe, and R. P. Sinha. Large steerable radio telescope at Ootacamund, India. *Nature Physical Science*, 230:185–188, April 1971. doi: 10.1038/physci230185a0.
- M. Tokumaru, T. Kondo, H. Mori, and T. Tanaka. Solar wind motion near the sun derived from simultaneous interplanetary scintillation observations at 2 GHz and 8 GHz. *Journal of Geomagnetism and Geoelectricity*, 46(10): 835–849, 1994.
- M. Tokumaru, M. Kojima, K. Fujiki, K. Maruyama, Y. Maruyama, H. Ito, and T. Iju. A newly developed UHF radiotelescope for interplanetary scintillation observations: Solar wind imaging facility. *Radio Science*, 46(5):RS0F02, 2011. doi: 10.1029/2011RS004694.
- B. Vršnak, D. Vrbanec, and J. Čalogović. Dynamics of coronal mass ejections. the mass-scaling of the aerodynamic drag. *Astronomy and Astrophysics*, 490:811–815, November 2008. doi: 10.1051/0004-6361:200810215.